J. Geophys. 41, 135–148, 1975

Originals Investigations

Seismic Investigations along the Scandinavian "Blue Road" Traverse

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Received May 2, 1974; Revised Version June 27, 1974

Abstract. At the end of July and the beginning of August 1972 seismic studies were carried out along the Scandinavian "Blue Road" traverse, an area of interdisciplinary geoscientific research. Geographically, it runs from the Norwegian coast, near the arctic circle, through Sweden into southern Finland, having a total length of about 600 km, passing through the Caledonian mountain chain and extending into the Baltic Shield within its central area of land uplift.

Velocity models of the crust and upper mantle were computed, based on very clear arrivals of refracted P-waves. The crust mantle boundary, which was mapped along the whole profile, shows only minor undulations. Reaching a depth of about 40 km on the Baltic Shield the Moho shows no distinct roots below the Caledonian mountains. A constant mantle velocity is derived, to depths of about 80 km, from parallel P_n-branches. Apart from different geological structures near the surface, the overall distribution of seismic velocities appears to be very similar within the Caledonides and the Baltic Shield.

Key words: Deep Seismic Sounding — Crustal Structure of Baltic Shield and the Caledonides.

Introduction

The Caledonian mountain range and the Baltic Shield form the northern part of the European continent. The Caledonides represent the remnants of an orogeny which took place between 700 and 400 m.y. B. P. (Lundegård *et al.*, 1970). The structure of the Caledonides indicates lateral compression and overthrust of nappes, eastward, on to the Baltic Shield, processes which probably took place on the col-

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lision or the subduction zone of drifting plates in accordance with the theory of plate tectonics. The Baltic Shield represents a very old tectonic unit and consists of remnants of ancient orogenies which took place in several cycles: the Svecofennian folding, covering the greater part of Sweden and southern Finland, took place between 2100 and 1500 m.y., the adjacent units to the north show increasing ages up to about 3000 m.y. (the Cola massiv, Welin, 1966, 1970), whereas the southern parts of Sweden are "only" 1400 to 860 m.y. old. There is considerable evidence that the Baltic Shield has been uplifted almost continuously since Caledonian times; the present and more recent land uplift is explained by isostatic compensation after the last ice-age (Haskell, 1935; Penttilä, 1969b).

About 18 seismic explosion investigations have already been carried out in Fennoscandia (Penttilä, 1969a, 1972). Most of the profiles were only about 200 km long and stayed in the same tectonic unit. Average *P*-wave velocities of 6.0 to 6.2 km/s for the "granitic" layer, values of 6.4 to 6.6 km/s for an intermediate crustal refractor, and 8.0 to 8.3 km/s for the mantle, have been found in different areas of Scandinavia. (Dahlman, 1967; Sellevoll and Pomeroy, 1968; Penttilä, 1969a, 1972; Båth, 1971; Kanestrøm, 1971; Vogel and Lund, 1971). The scatter of these data was small suggesting a rather uniform structure of the whole crust.

Following a recommendation of the European Seismological Commission in Luxembourg 1970, the Department of Solid Earth Physics at the University of Uppsala set out plans for an interdisciplinary investigation along a traverse, including a seismic profile from the Norwegian coast through Sweden, across the Gulf of Bothnia and into Finland. Starting at Mo i Rana the profile crosses the Caledonides, runs along the river Ume Älv, goes across the Gulf of Bothnia between Umea and Vaasa, and continues for 100 km inside the Svecofennian Shield of Finland. In Sweden, the profile follows the well known tourist route called the "Blue Road". Five shot points, with an average distance of 100 km, were planned for this 600 km long "lithospheric profile". At first, a multiple coverage of refractors was arranged by a system of reversed shots in order to obtain accurate physical parameters of crust and upper mantle over a longer range, and in two fundamentally different areas: the Caledonides in the north-west, and the Baltic Shield in the south-east, including the zone of maximum land uplift (Fig. 1).

Seismic Field Work

Seismic field work was carried out between July 28th and August 4th, 1972. Explosive charges equivalent to 700 kg TNT were fired, in the ocean at shot point 1, in small lakes at shot points 2, 3 and 4, and in the Gulf of Bothnia at shot point 5. Explosions at shot point 2—5 were prepared by the Research Institute of the Swedish National Defence, and those at shot point 1 were arranged by the Seismological Institute in Bergen. 42 recording units, MARS 66, for land stations were collected from geophysical institutes in Berlin, Bochum, Clausthal, Frankfurt, Görttingen, Hamburg, Hannover, Karlsruhe, Kiel, München, Münster, Stuttgart und Uppsala, one additional land station from the Institute of Seismology in Helsinki and three sea stations from the Geophysical Institute in Hamburg. Two series of four shots per night were recorded at 46 field stations along the profile. 42 MARS stations were equipped with multiplex FM modulators, three 2 Hz geophones, and a radio receiver.

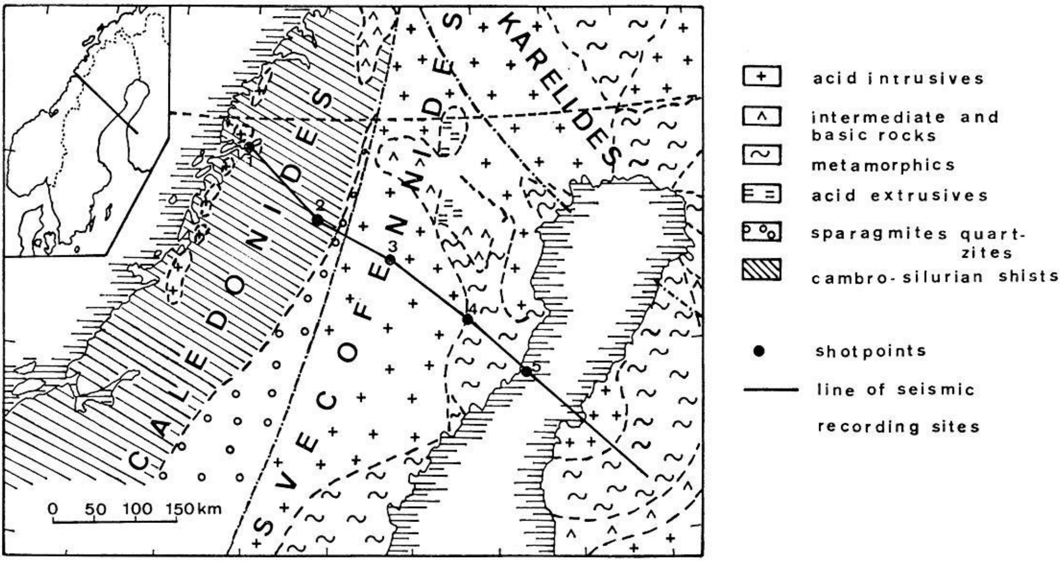


Fig. 1. Simplified geological map with profile and location of shot points; geologic data after Bundesanstalt für Bodenforschung and Unesco (1966)

Every third station was set up as a three component geophone array, the others with vertical geophones, about 400 m apart. The average spacing between stations was about 4 km. The whole field arrangement may be seen in Fig. 2. The sea stations were equipped with hydrophones on the seafloor. The seismic FM signals were transmitted from anchored sono-buoys to receivers on a nearby island. Time signals and radio announcements were provided by the Swedish radio network from a communication centre maintained by the Research Institute of Swedish National Defence. Two series of four shots each were fired within two nights of recording. During the first night of operation (spread A in Fig. 2) 36 land stations were arranged with equal spacing between shot points 3 and 5 (in the Swedish part of the Baltic Shield), two sea stations and one land station in the Gulf of Bothnia and five land stations in Finland, recording signals from shot points 1, 3, 4, 5, using 1400 kg TNT at shot point 3. In the second night of recording (spread B in Fig. 2) 37 land stations were arranged between shot points 1 and 3; one station remained on an island in the Gulf of Bothnia and one sea station remained on its former position; two sea stations and five land stations in Finland moved to greater distances. In this second night of operation shots at shotpoints 1, 2, 3 and 5 were fired, using 1400 kg TNT at shotpoint 5. After each night of recording field crews working in Sweden and Norway met at the operational centre at Storuman for the play-back of recorded data and for further information on the operations. A total of four reversed sections, each about 100 km in length, two reversed, each about 200 km in length, and one of about 400 km were obtained. In addition, several unreversed sections of 200 km and more were observed by the stations operating in Finland and the Gulf of Bothnia; the largest recording distance was about 600 km. The quality of the data, due to low noise level and favourable weather, was extremely good.

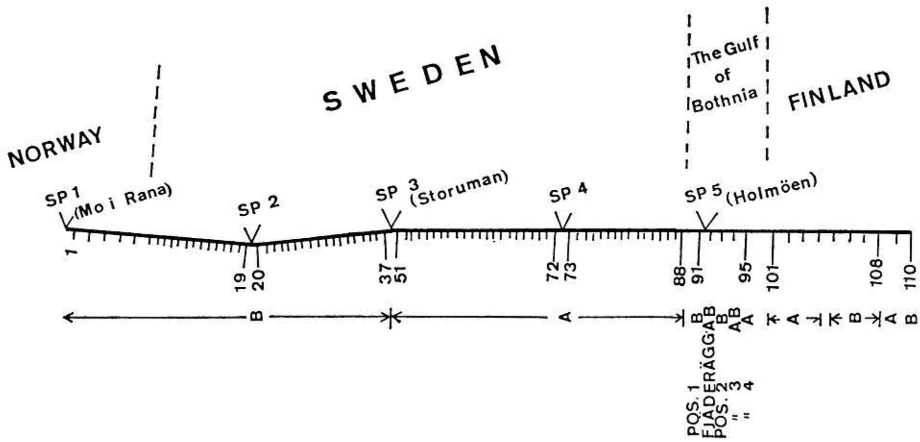


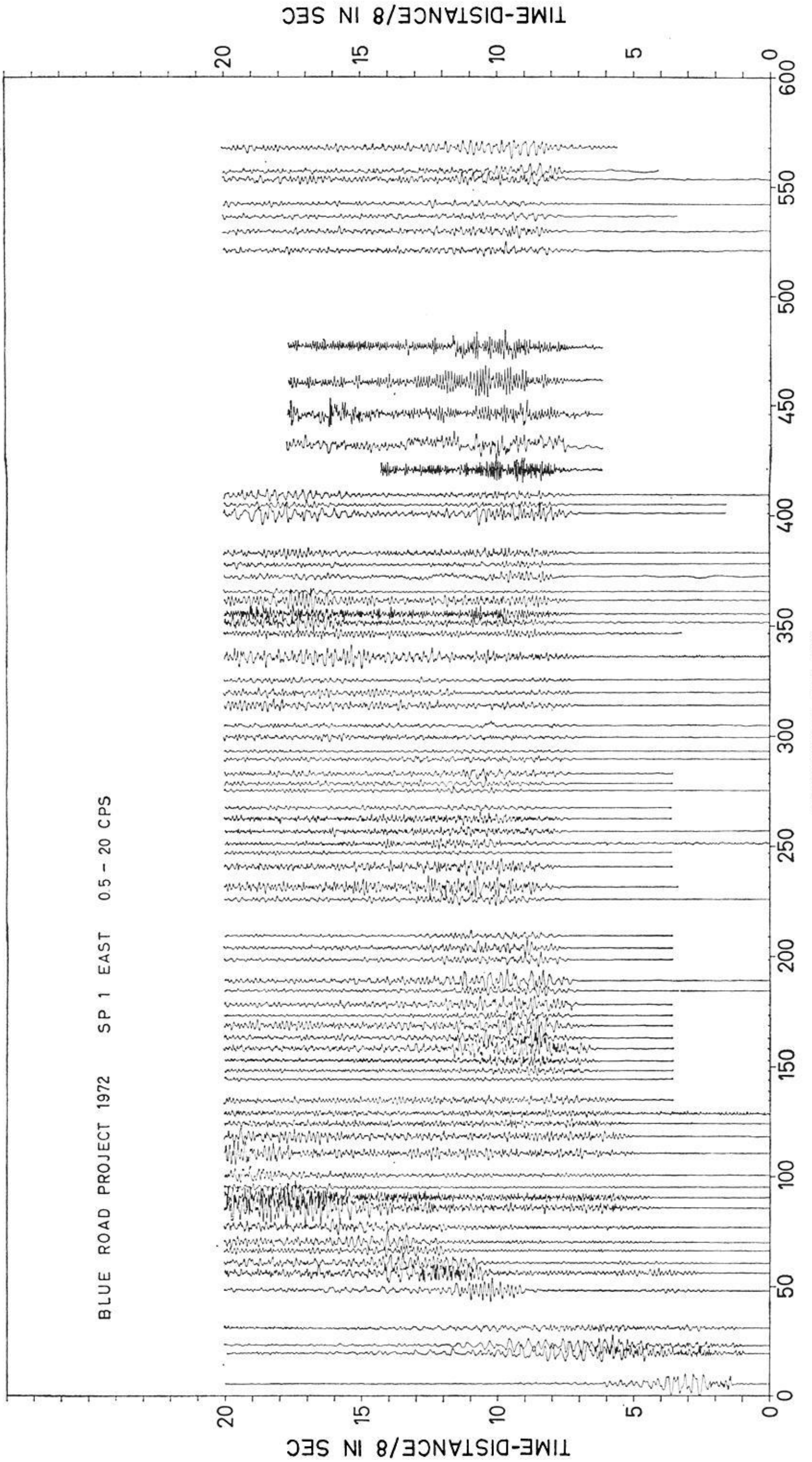
Fig. 2. Arrangement of shotpoints and recording stations along the profile

Interpretation

Analog or digital processing was applied to the data. This information was then compiled into seismogram sections after being filtered by a band pass of 1 to 20 Hz. Fig. 3 to 7 show nine sections, each reduced with a velocity of 8.0 km/s in order to draw attention to the P_n-waves. Although excellent first arrivals were found along the whole profile, secondary arrivals were generally weak. No clear wide angle reflections have been detected although some indications were observed at distances of 120—250 km on profiles 1-East, 3-East and 5-West. Thus, reflection observations could not be used in converting travel-time curves into velocity-depth functions.

In general, only first arrivals were evaluated, and a ray tracing program after G. Mueller (1971, unpublished) was used in order to calculate theoretical traveltime curves. Velocities were considered as a function of depth. In general, velocities in the upper part of the crust increase continuously, or discontinuously, from 5.7 to about 6.2 km/s. Velocities between 6.0 and 6.2 km/s characterize the layers down to about 15 to 20 km. Below these depths velocities around 6.5 to 6.8 km/s are found for the deeper crust below all shot points. The Mohorovičić discontinuity (= Moho) is found between 37 and 40 km in the region surrounding the five shot points (Fig. 8).

The theoretical travel-time curves of these velocity-depth functions are in close agreement with the observed first arrivals. As a consequence of these velocity models, however, one should expect secondary arrivals, such as reflected and refracted waves from the first order boundaries. As definitely only small cusps in the travel time behaviour are observed, one has to look for more refined models. Secondary arrivals on seismogram sections 1-East and 5 West forming a cusp do not show apparent velocities (v_a) larger than 8 km/s. This means that no subcritical reflections from the Moho with $v_a > 8$ km/s are observed, and hence, most probably, no first order interface with a considerable increase of velocity values exists at the crust-mantle boundary. Velocity-depth models without a significant first order disconti-



Figs. 3–7. Record sections

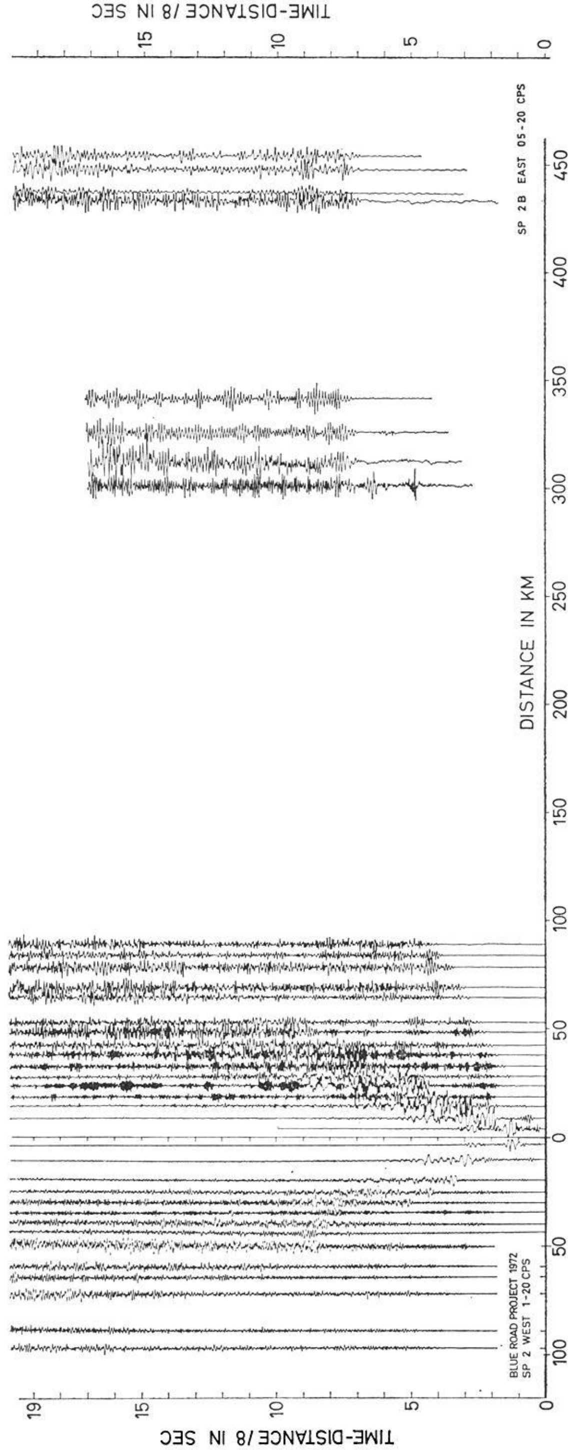

TIME-DISTANCE /8 IN SEC
DISTANCE IN KM
SP 2 B EAST 05-20 CPS
BLUE ROAD PROJECT 1972
SP 2 WEST 1-20 CPS
TIME-DISTANCE /8 IN SEC

Fig. 4

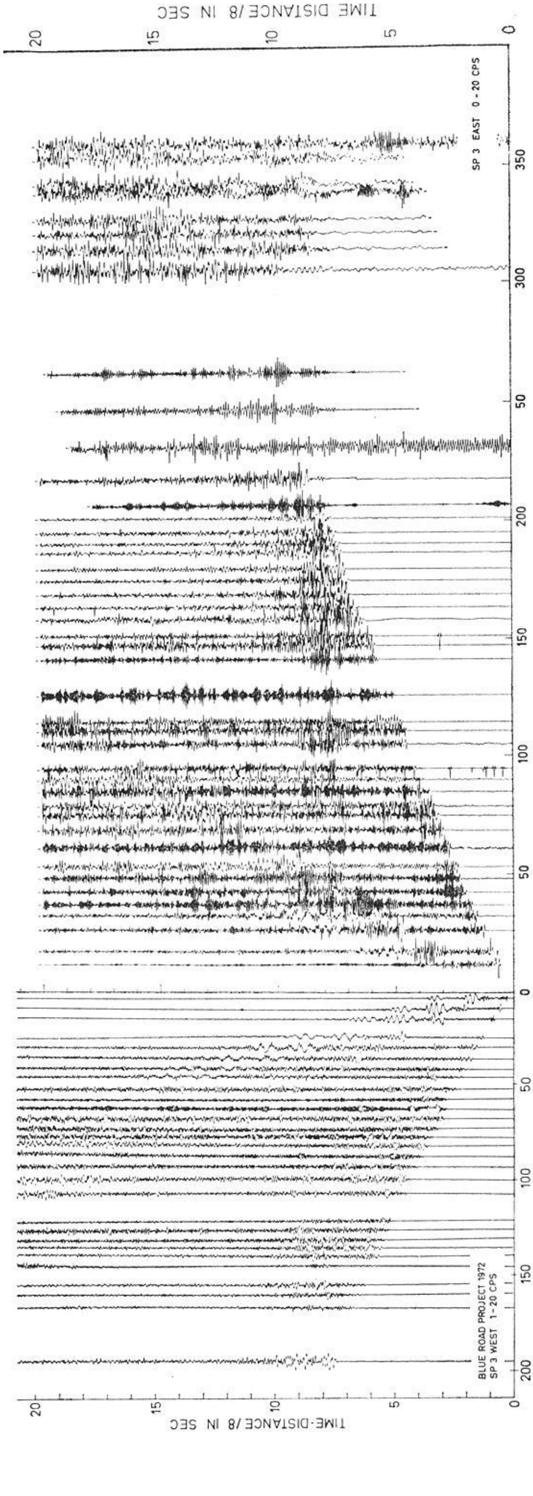

TIME-DISTANCE/8 IN SEC
SP 3 EAST 0-20 CPS
DISTANCE IN KM
BLUE ROAD PROJECT 1972
SP 3 WEST 1-20 CPS
TIME-DISTANCE/8 IN SEC

Fig. 5

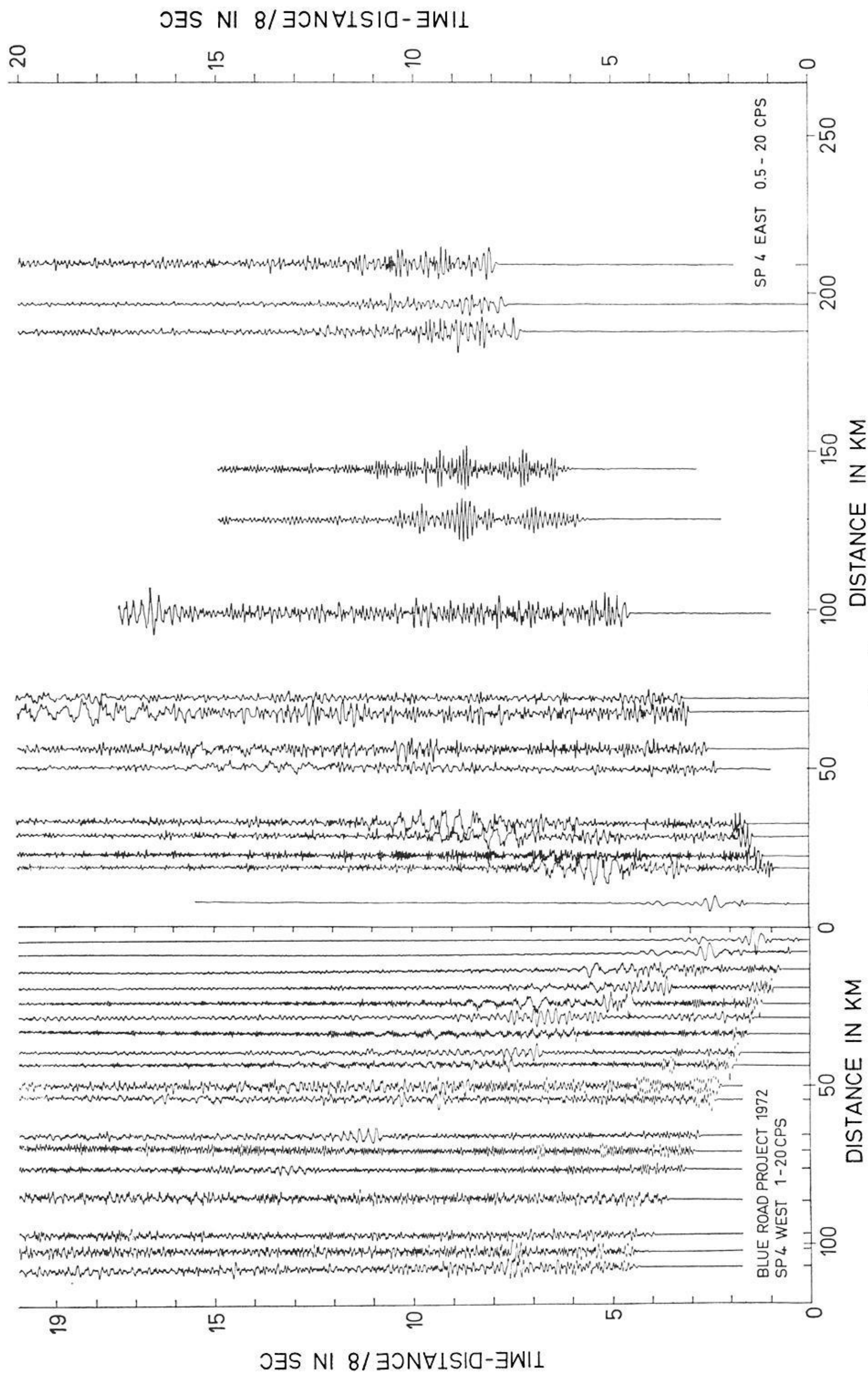

TIME-DISTANCE/8 IN SEC
SP 4 EAST 0.5 - 20 CPS
DISTANCE IN KM
BLUE ROAD PROJECT 1972
SP 4 WEST 1-20 CPS
DISTANCE IN KM
TIME-DISTANCE/8 IN SEC

Fig. 6

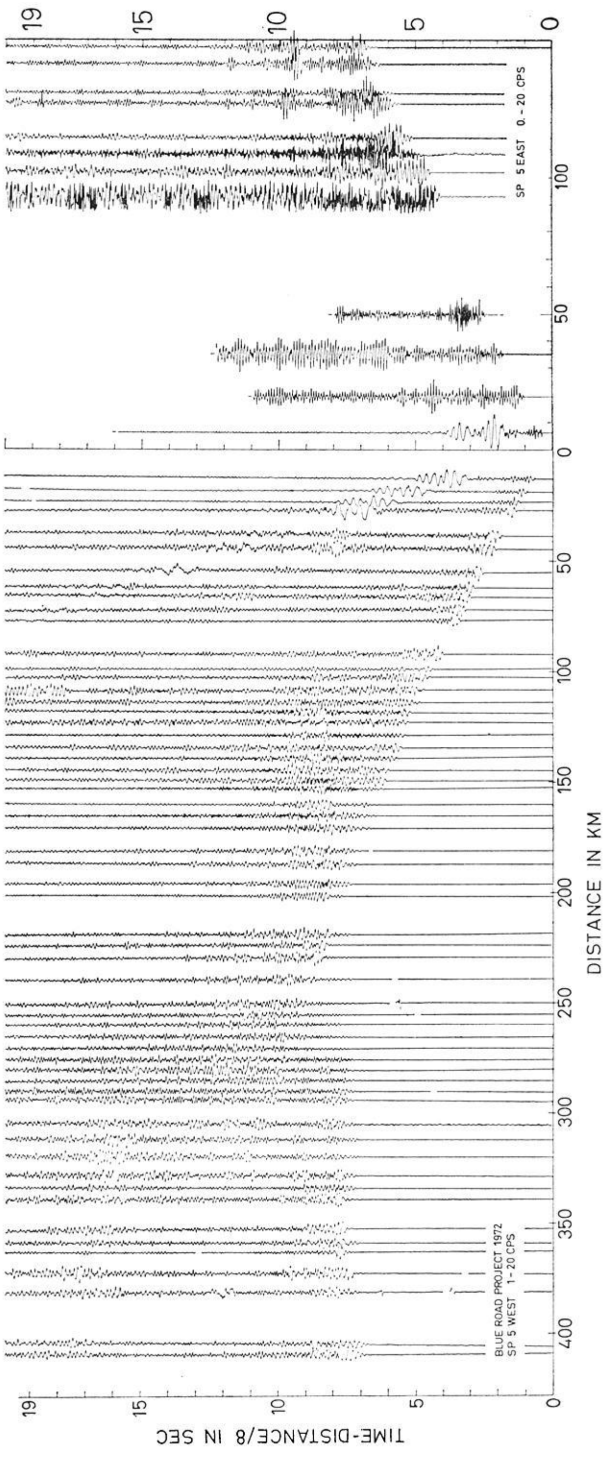

SP 5 EAST 0.-20 CPS
BLUE ROAD PROJECT 1972
SP 5 WEST 1-20 CPS
DISTANCE IN KM
TIME-DISTANCE/8 IN SEC

Fig. 7

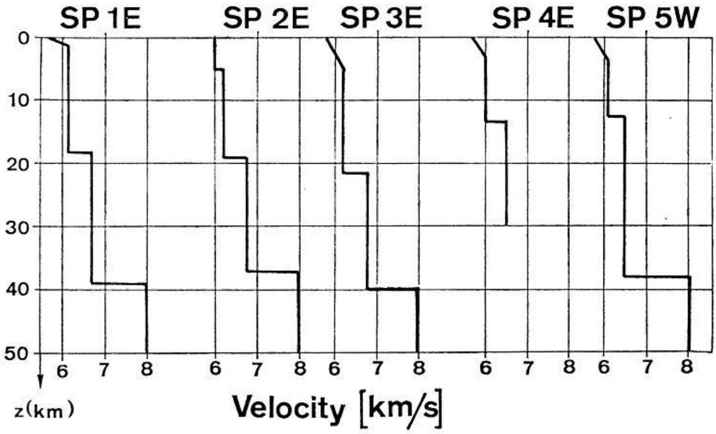


Fig. 8. Velocity-depth functions with best fit of theoretical to observed travel-time curves along the profile

nuity should certainly be given preference. Fig. 9 shows the seismogram section 5-West with the theoretical travel-time curves of a best fitting gradient model with only a small first order boundary at the base of the crust; (note the cusp between 130 and 260 km). In general crustal thickness is increased by a model including gradients. From first arrivals only weak indications are found for the existence of a Conrad boundary in the depth range between 12 and 20 km. It cannot be decided whether they represent a small first order discontinuity or a general smooth increase to velocity values of 6.6 to 6.8 km/s.

There is no indication for a low velocity channel in the crust. The P_n-arrivals from the Moho particularly show many variations of the apparent velocity along the profile. In most cases, recordings of additional P_n-arrivals from the same part of the profile permit a direct correlation between these velocity variations and the dip of the Moho. This is especially reliable for the area between 170 and 280 km south-east of shot point 1, where a complete coverage of the Moho surface by reversed-profiles has been achieved. As there is a twofold of threefold coverage of the Moho by refracted arrivals from different shot points, the apparent velocities of these arrivals can be controlled. It was a surprise that apparent P_n-velocities from various distances, such as 500 to 600 km and 150 to 250 km turned out to be exactly the same. This means that there is no positive velocity gradient in the first 50 km of the upper mantle[1].

With the continuous coverage of the Moho a cross section along the whole profile was obtained. The velocity models mentioned before were used in order to apply wave-front methods for the calculation (Meissner, 1965). Wave-fronts and depths were plotted by a computer program based on well known ray equations for media with constant velocities and continuous series with constant velocity gradients. Generally, Moho depths coincide with those of the ray tracing models. At some

1 One of us (C.-E. Lund) does not agree with these conclusions and plans to publish a separate paper on this subject.

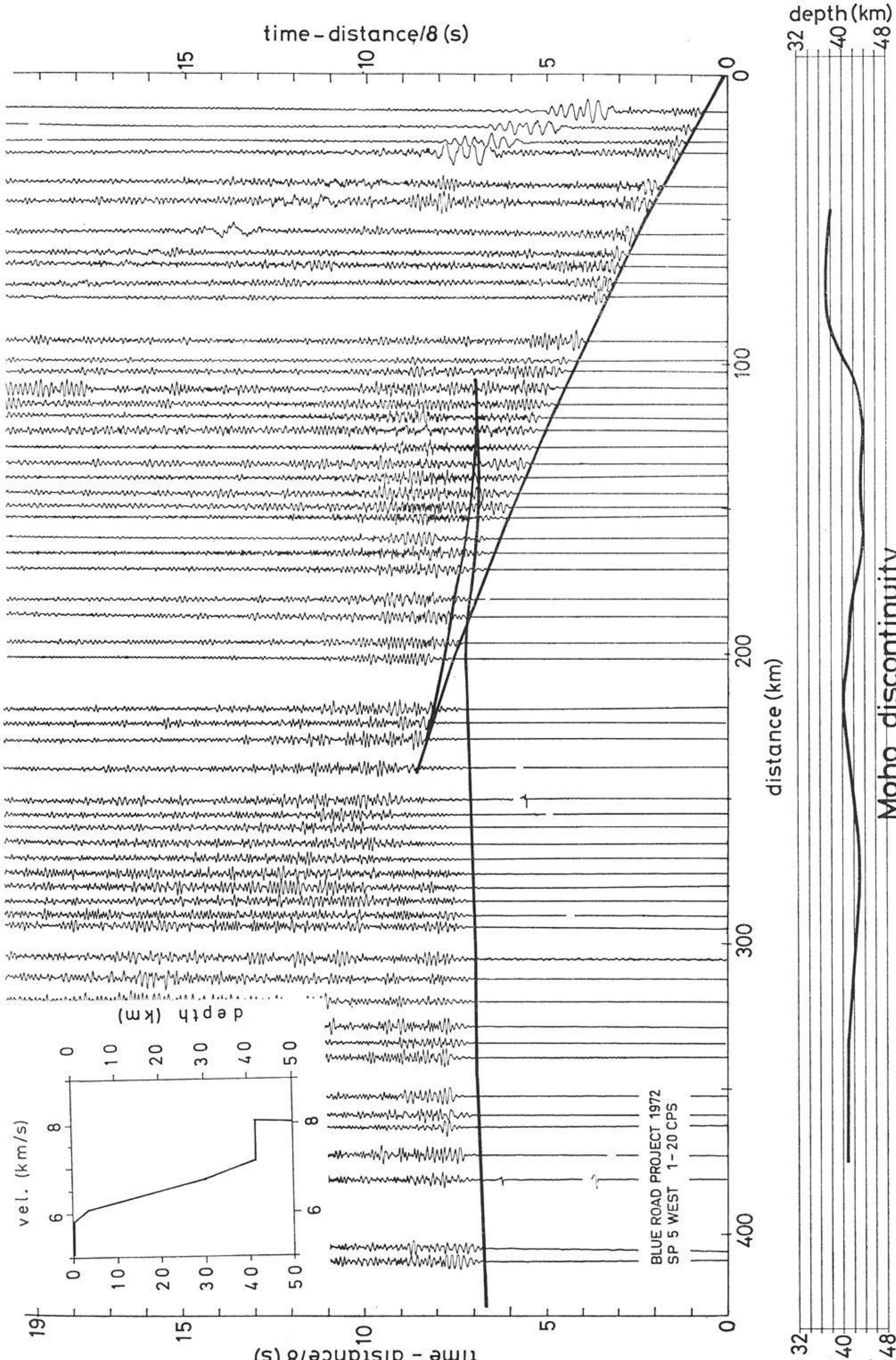


Fig. 9. Seismogram section 5-West with the theoretical travel time curves of a gradient model

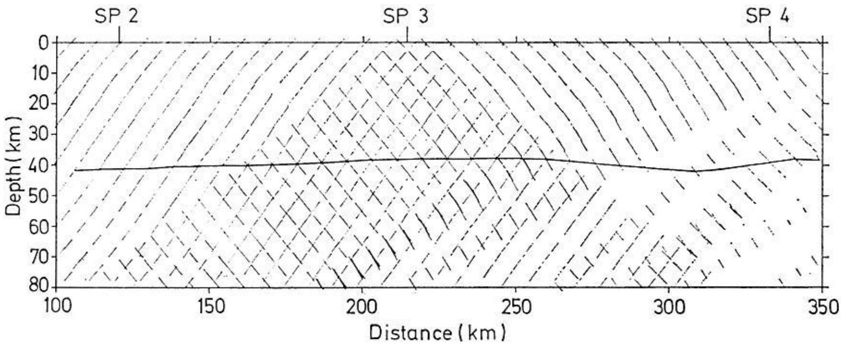


Fig. 10. Computer plot of wave-front diagram and construction of the Moho between 150 and 260 km

single points, however, small differences of about one km occurred, because the depth data from the models are based on average travel time curves, neglecting dips and being accurate only at a certain distance from the shot point. Wave-front constructions, on the other hand, are most reliable for the area between 170 and 280 km where a reversed coverage was achieved. The true upper mantle velocity obtained here is 8.15 $\pm$ 0.02 km/s. Fig. 10 shows an example of wave-fronts and Moho depths in this area. In the other regions of the profile this velocity was used in fitting segments of length $\Delta s = V_n \, \Delta t$ between plotted wave-fronts. Assuming slightly different V_n-velocities in these areas, some small deviations in depth might arise. They are limited, however, by the model calculations mentioned above and by the small amount of scatter of available P_n-velocity values in Scandinavia.

The best wave-front construction of the Moho for the whole profile is presented in Fig. 11. This section also shows the mean topographic heights along the profile. Large crustal depths were found on the south-east slope of the Caledonian mountain system, the Moho being 42 km deep. Depths stay quite constant along the transition to the Baltic Shield in Sweden with a small anticline bringing the Moho to a depth of 37 km about 60 km north-west of the shore of the Gulf of Bothnia. Below the south-eastern part of the Gulf of Bothnia a maximum depth of 44 km is found.

Whereas depths and undulations of the Moho could accurately be mapped, those of other boundaries, inside the crust, could not be plotted with the same reliability. They have, however, been included as dashed lines in Fig. 11, in order to give a general idea of possible changes in seismic parameters at the indicated depth levels. General geological data are also plotted along the profile. No significant lateral changes of velocity or other physical parameters were detected.

Conclusions

The crust-mantle boundary appears as a smooth, unfaulted discontinuity, crossing various tectonic areas which seem to be welded together. Seismic models from shot points 1, 2, and 3 show no basic difference. The seismic structure of the crust and the crust-mantle boundary do not indicate isostatic compensation of the Caledonian mountains. Negative Bouguer anomalies in the mountain area, however,

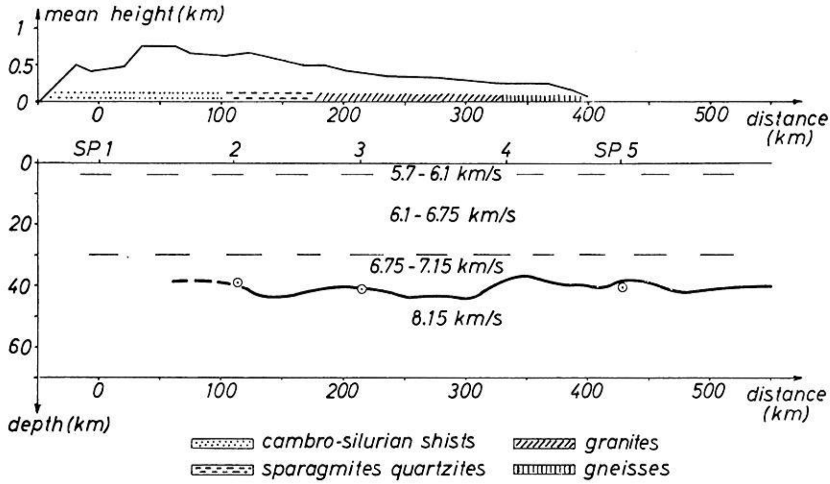


Fig. 11. Crustal cross-section along the profile Upper part: Topographic profile, exaggerated 1:60, with main geologic structures Lower part: Seismic boundaries, exaggerated 1:1,5, with velocity values in km/s

point to compensating mass deficiencies. It seems that the mass distribution in the asthenosphere contributes significantly to the isostatic compensation of the Caledonian mountain range.

There is no positive velocity gradient in the upper mantle. P_n-arrivals from various distances are exactly parallel. This means that, at least down to depths of 80 km, the same velocity and hence most probably the same density and material are found in the upper mantle[2]. A kind of Conrad discontinuity may be mapped by introducing a first order boundary in the north eastern part of the Gulf of Bothnia. Preference is given, however, to velocity-depth functions indicating a smooth transition zone in the crust between 20 and 25 km in depth, as shown in Fig. 9. No crustal low velocity layer is observed. Neither have continuous reflected waves P_m along the profile been found. Only some secondary arrivals have been detected consisting of supercritical reflections and diving waves. No subcritical reflections with $V_a > 8$ km/s have been found, which supports the idea of gradient zones instead of strong first order boundaries. This nearly complete absence of good P_M-arrivals in the Caledonides and the shield areas during these and previous investigations is hard to understand in view of the excellent signal to noise conditions. It is tentatively suggested that the reflection coefficient at the Moho must be rather small owing to i.) a concentration of grabboic and denser material in the lower crust, and/or ii.) and extended zone of small velocity gradients, similar to the model shown in Fig. 9, at the base of the crust, or/and iii.) low velocity zones and lamelles being absent in this area.

Only slight seismic evidence has been found for the nearly continuous uplift of the Fennoscandian Shield since the Palaeozoic. One indication is that sediments are

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2 See footnote page 144.

missing. Another indication is the presence of rather high velocities, such as 6.6 to 6.8 km/sec, at comparatively shallow depths, around 20 km. Assuming the Moho as a chemical boundary, it seems probable that it, too, has been uplifted during the last 400 m.y., a process which apparently has not resulted in overthrusting or strong faulting, but only in gentle undulations. Apart from structures near the surface, the earth's crust along the profile seems to represent a uniform tectonic unit.

Acknowledgements. The "Blue Road" seismic experiments were mainly supported by the Swedish Natural Science Research Council and the Deutsche Forschungsgemeinschaft. Also funds from Norwegian and Finnish sources have been contributed to the project.

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